Cover page

Title: Modelling the Fire Resistance of Prestressed Concrete Floors using Multi-Spring Connection Elements

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ABSTRACT

Despite big advances in analytical modelling of the performance of structures exposed to fire, there has been difficulty in modelling the fire performance of precast prestressed concrete floor slabs in multi storey buildings. The fire resistance of these floor systems is heavily influenced by the end connections and the stiffness of the surrounding structure, both of which must be considered in any analysis.

Previous "traditional" studies have modelled the floor slabs with beam or shell elements in which the end nodes share the nodes of the beam elements representing the supporting beams. This is acceptable for cast-in-situ or precast flooring system without prestressing, but leads to a major problem for precast prestressed flooring systems where the steel tendons terminate at the end of the flooring units, because the approach of sharing nodes of the supporting beam and floor assumes that these tendons are anchored into the supporting beams.

In order to solve this problem, a "multi-spring" connection element has been developed. The multi-spring connection element consists of several parallel axial springs sandwiched between two rigid plates. Each spring represents either a steel reinforcing layer or a segment of concrete in the floor cross-section. The concrete springs have compression-only properties. This multi-spring connection is placed between the end nodes of the floor and the nodes of the supporting beam. With this element, it is possible to terminate the prestressing tendons at the end node of the floor elements and to anchor only the topping reinforcement into the supporting systems predicted using the traditional approach and the newly developed multi-spring connection, with applications to different forms of precast concrete floors in multi storey buildings.

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INTRODUCTION

The use of precast prestressed concrete flooring systems in multi-storey buildings has become very common in New Zealand due to several advantages, such as high quality control and the saving of labour. Recently, a considerable number of studies [1], [2], [3], [4], [5] have been conducted on the structural performance of precast prestressed concrete flooring system against earthquake actions at ambient temperatures. Nonetheless, relatively little attention was paid to fire performance of prestressed concrete flooring building systems [6], [7], [8].

The hollowcore concrete slabs, one of the most widely used prestressed concrete flooring systems in multi-storey buildings, has been studied by a few researchers [9], [10]. The studies, which were only limited to single or two units, have shown that some failure modes, such as debonding, shear and spalling, are more critical in prestressed hollowcore concrete slab exposed to fire. In addition, finite element models, including shear and anchorage failures, have been developed to improve understanding with regard to hollowcore concrete slab. The failure mode of hollowcore slab exposed to fire has recently been questioned by some full-scale frame tests [6], [8] carried out at the Building Research Establishment (BRE) Cardington test facility in the UK. According to the BRE results of a series of full-scale frame test on hollowcore floors, the fire performance of hollowcore floors in a full-scale frame exposed to serious fires was satisfactory and there was no premature failure or shear failure or significant spalling.

Despite big advances in analytical modelling of the performance of structures exposed to fire, there has been difficulty in modelling the fire performance of precast prestressed concrete floor slabs in multi storey buildings. The fire resistance of these floor systems is heavily influenced by the end connections and the stiffness of the surrounding structure, both of which must be considered in any analysis.

Previous studies [11] have modelled the floor slabs with beam or shell elements whose end nodes share the nodes of the beam elements representing the supporting beams. This is acceptable for cast-in-situ or precast flooring system without prestressing, but leads to a major problem for precast prestressed flooring systems where the steel tendons terminate at the end of the flooring units, because the approach of sharing nodes of the supporting beam and floor assumes that these tendons are anchored into the supporting beams.

This paper presents the development of a multi-spring connection element which is able to take into account the discontinuity of prestressing steel tendons between hollowcore slabs and their supporting end beams. The multi-spring connection elements model is verified against experimental data from furnace tests on hollowcore slabs connected to end beams obtained from literature.

TYPICAL STRUCTURAL CONNECTION DETAILS OF PRESTRESSED HOLLOWCORE SLAB

Precast prestressed hollowcore floor units seated on reinforced moment resisting frames have been widely used as one of most common construction types in New Zealand during the last few decades. In order to investigate the seismic adequacy in different construction types, a series of experiments have been performed so far [1],

[2], [3]. As a result, two acceptable solutions for hollowcore seating connections have been implemented in Amendment 3 within NZS3101:1995 and NZS3101:2006 for 'new' construction practice in New Zealand [4].

Simple connection detail

Traditionally, simply supported precast prestressed hollowcore slabs in New Zealand have been widely used as shown in Figure 1 [12], [13]. The simple connection details comprised of the floor unit seated on a mortar bed, core end plugs to prevent concrete from entering the cores, and conventional starter bar reinforcement in the topping slab [1]. As shown in the figure, a hollowcore slab is not directly anchored to the supporting beam; only the starter bars from the topping concrete are connected to the supporting beam. In a typical seating detail, the starter bars connected between topping slabs and supporting beams provide rotational restraint and allow some redistribution of the bending moments in the slabs [13]. The gap between the supporting beam and the hollowcore slab is filled with normal concrete in order to provide flexibility of lateral movement for earthquakes.

Continuous connection detail

While the simple connection detail of prestressed hollowcore floors has been widely used, a rigid continuous floor-end beam connection solution has been proposed in order to improve seismic performance as shown in Figure 2. This continuous connection features hollow cores reinforced and filled with concrete [3]. For 200 mm deep hollowcore slabs, two cores of the six hollow cores are reinforced with hooked bars placed close to the bottom of the cores. The topping slab consists of reinforcement which is lapped with the starter bars. To construct the continuous connection, more effort, such as pre-cutting of cores and placing of extra reinforcement, are required in comparison to simple connection detail. However, the continuous connection provides redundancy by being tied into the supporting beams [3].

MODELLING OF PRECAST PRESTRESSED FLOORS FOR FIRE ANALYSIS

General

Special purpose, non-linear finite element program, SAFIR [14], which has been developed at the University of Liege, Belgium and is capable of conducting both thermal and structural analysis of structures, was used to carry out this numerical analysis. It includes two different types of elements which are used in this study: beam and spring elements.

Structural elements

The beam element has a constant section along the longitudinal axis that is a straight line extending between the two end nodes. In previous research [11] a beam

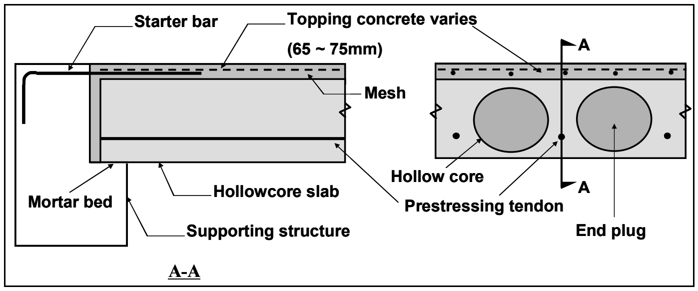


Figure 1. Simple floor-end beam connection detail of hollowcore floors

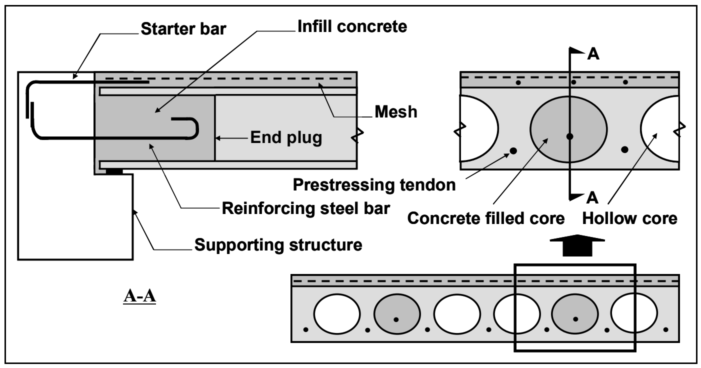
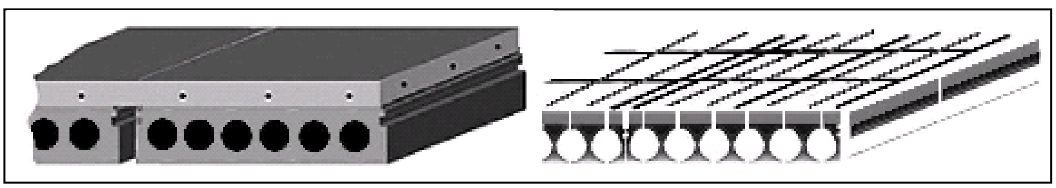


Figure 2. Continuous connection detail of hollowcore floors



(a) Solid model (b) Grillage model

Figure 3. Grillage system for hollowcore system and topping concrete

grillage system was used to model the hollowcore units and shell elements was used for the topping concrete, whereas topping concrete is incorporated into the beam grillages in this study, as shown in Figure 3. Detailed information on the beam grillage model of hollowcore slabs can be found in reference [7], [11], [16].

Limitations of SAFIR

Material models included in SAFIR program have some inherent assumptions, as is the case with all analytical models. The possible limitations of SAFIR resulting from these assumptions are:

1) SAFIR assumes perfect bond between two materials and cannot account for slippage between concrete and the steel.

2) SAFIR cannot predict spalling of concrete.

3) Because SAFIR is based on the Bernoulli hypothesis, the beam finite element cannot detect shear failure.

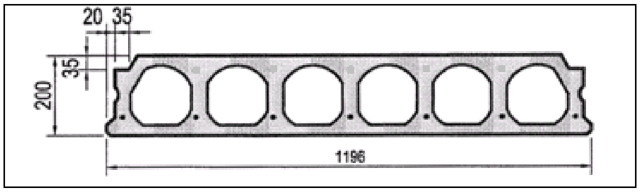


Figure 4. Cross-section of a 200 mm hollowcore unit

TABLE I. PROPERTIES OF THE HOLLOWCORE FLOOR UNIT

Hollowcore	Cross-sectional area	0.121 m^2
	Self weight	3.88 kPa
	Compressive strength	45 MPa
Prestressing strands	Type	Stress relieved 7-wire strand
	Strength	1.87 GPa
	Prestressing level	70%
	Cross-sectional area/strand	100 mm^2
Reinforced concrete topping slab	Concrete compressive strength	30 MPa
	Reinforcement strength	450 MPa

Dimensions and material properties

A typical 200 mm deep and 1200 mm wide prestressed hollowcore unit is shown in Figure 4 while the properties of such units are listed in Table 1.

DEVELOPMENT OF MULTI-SPRING CONNECTION MODEL

As explained in Section 2, current New Zealand has two different types of connection details. Analytical models for both connection details are developed in this study.

Multi-spring connection model for simple connection detail

A schematic of the multi-spring model for simple connection is shown in Figure 5. In using the grillage model, beam elements, as shown in Figure 5, are expressed as fibres which include the geometrical and mechanical properties of the hollowcore cross-section as well as its thermal properties at elevated temperature. Here, the vertical faces in either side of the gap between the hollowcore slabs and seating beams are modelled as rigid surfaces, which are connected to each other through a series of springs of representing concrete and the starter bars. The use of rigid beam elements is able to avoid unnecessary small displacements at the vertical faces. Both rigid faces are vertically supported at the bottom, but the internal face is allowed to move horizontally and rotate freely to capture the variation of the gap at the end of the hollowcore slabs. On the other hand, the external rigid beam element at the vertical surface of the seating beam can be assumed to be either fully fixed at the end boundary or connected to the supporting beam depending on the conditions.

In order to employ spring elements into the new connection model, the cross-section of the gap between hollowcore slabs and seating beams is divided into nine segments as shown in Figure 6. In SAFIR, the geometry of the spring elements is determined by the position of the two end nodes and spring elements are completely

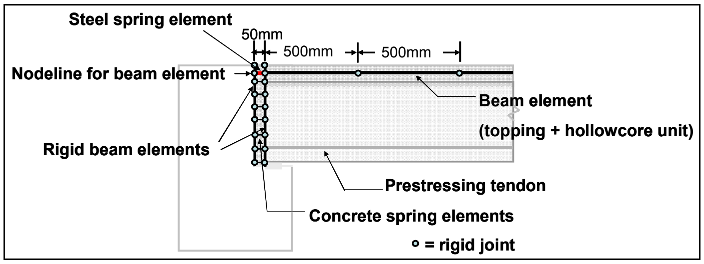


Figure 5. Schematic of multi-spring connection model for simple connection detail

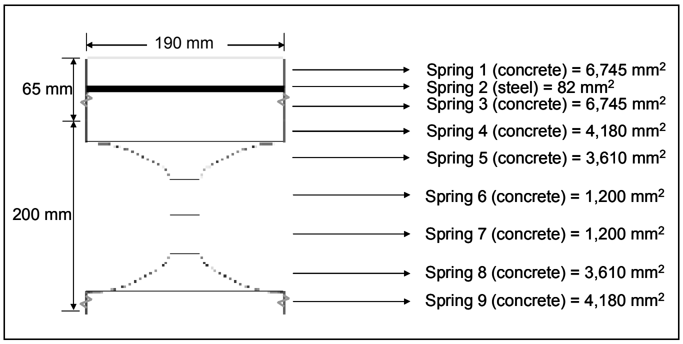


Figure 6. Division of the hollowcore slab cross-section for simple connection (white segment: concrete; black segment: steel)

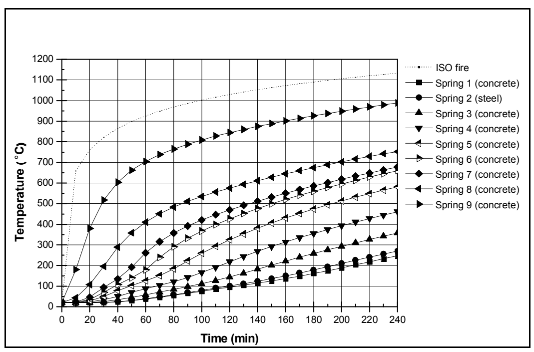


Figure 7. Temperature variation of each spring element for simple connection

defined by their cross sectional areas and the material types. The temperature developments obtained from thermal analyses, as shown in Figure 7, are applied to each of nine spring elements.

Multi-spring connection model for continuous connection detail

Most details of the multi-spring model for continuous connection detail are principally based on the multi-spring connection model used for simple connection detail. Continuous connection detail has some differences compared to the simple connection detail. Two steel spring elements (second from top and third to bottom spring elements) were used to model the starter bar and reinforcing bar within the core. In current connection detail, the gap between the hollowcore slabs and the end beams is filled with concrete. Area of the spring elements, therefore, is modified as

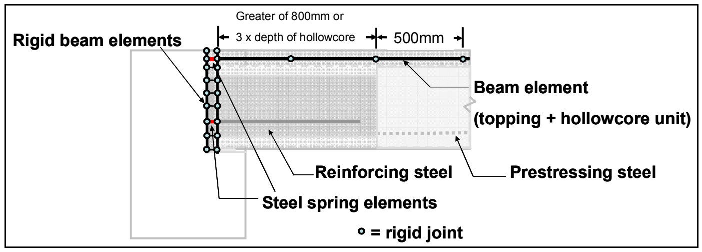
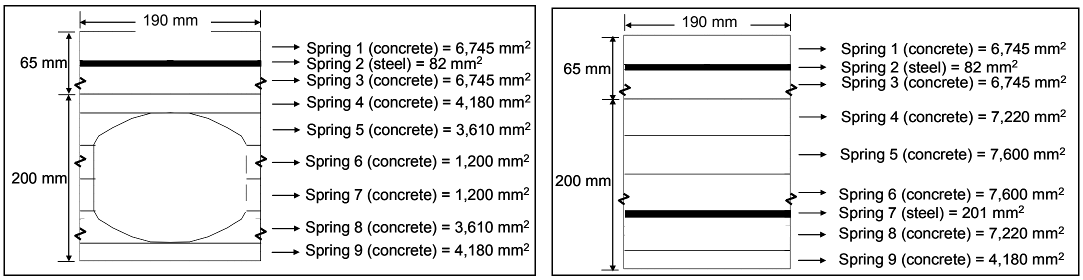
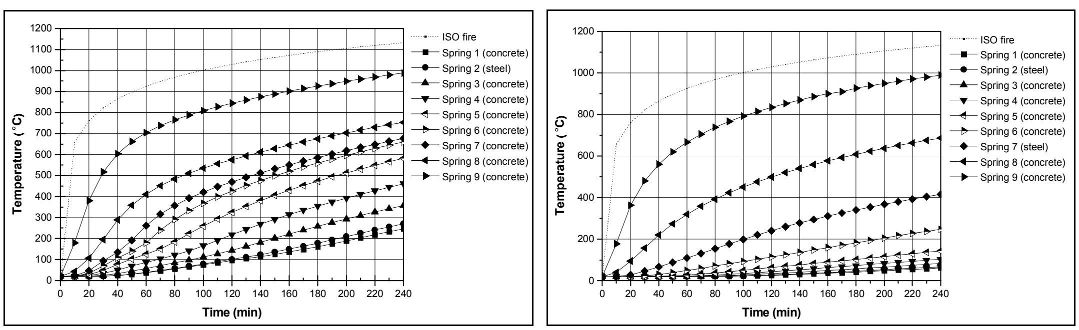


Figure 8. Schematic of multi-spring connection model for continuous connection detail



(a) cross-section with unfilled core (b) cross-section with filled core

Figure 9. Division of the hollowcore slab cross-section for filled and unfilled core of current connection (white segment: concrete; black segment: steel)



(a) unfilled core (b) filled core

Figure 10. Temperature variation of each spring element for continuous connection for unfilled and filled core

shown in Figure 9. Due to the filled concrete in the voids, there is a change in terms of temperature assessment. Figure 10 shows the temperature developments of the modified spring elements.

Comparison of traditional approach with the developed multi-spring connection model

The structural behaviour of a prestressed 200 mm hollowcore slab unit, which is restrained against horizontal and vertical movements at the end supports, is numerically investigated with and without the multi-spring connection elements. The analysis with fixed-fixed end supports based on traditional approach assumes that the prestressing strands in the hollowcore slab are anchored in the supporting beams. Figure 11 shows the comparison of structural behaviour in fire between the traditional approach and the newly developed multi-spring connection models. The mid-span vertical displacement for the fixed-fixed end condition suddenly increases after 60 minutes and then stabilises to a slow but gradual increase without any sign of failure up to 4 hours. This unconvincing response does not happen in reality because the analysis with fully fixed end supports give rise to catenary action after the failure of starter bars when the hanging slab is supported by the tensile capacity of the prestressing steels anchored to the fixed supports. On the other hand, the newly developed multi-spring connection models resulted in failure after 62 and 87 minutes respectively. Therefore, the comparison of results indicates that the multi-spring connection elements model is more appropriate than the traditional approach because the displacement predicted by the multi-spring connection model shows a more realistic trend of the slab deflection with time.

VALIDATION AGAINST EXPERIMENTAL DATA

Four full-scale fire tests were performed at the Technical Universities of Liège and Gent in Belgium, taking into account the influence of connections and surrounding structures on the fire resistance of prestressed hollowcore slabs. Among these test results, one fire test result [17] which includes reinforced topping slab, as shown in Figure 11, has been chosen to validate the multi-spring connection model. The connection features two of the six hollow cores reinforced and filled with concrete. Even though the test consisted of 2 prestressed hollowcore floor spans of 6 m with three supporting beams, only 3m one span was covered with reinforced topping slab.

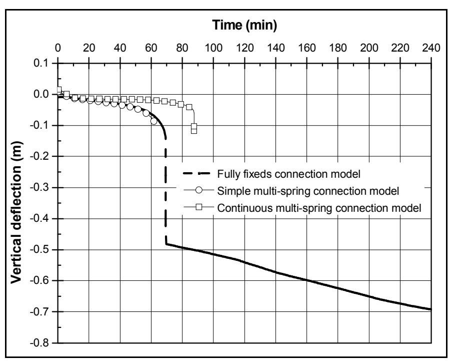


Figure 11. Comparison between vertical deflections of with and without the multi-spring connection model with respect to Fixed-Fixed end conditions

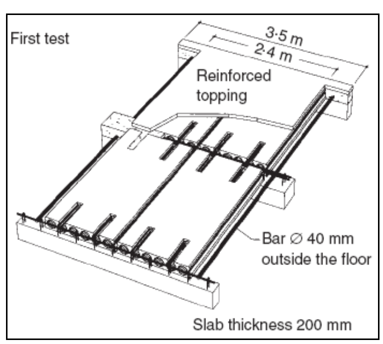


Figure 11. Fire test set-up [17]

The hollowcore units were 200 mm thick with a 50 mm thick reinforced topping slab and the cross-section and dimensions are shown in Figure 12. As mentioned earlier, every third core was filled near the supporting beams, and four 500 mm long bars of 12 mm diameter were cast in these cores and anchored in the supporting beam. A reinforcement mesh of 150 x 150 x 4 mm was cast over half of the test floor. The reinforcing bars of 40 mm diameter which were used to simulate the influence of the neighbouring structure were not considered in this analysis. The cube strength of the joint concrete and topping was 45 N/mm^2. The imposed load for the test was a line load of 100kN in the middle of each of the two spans. The fire test was interrupted after 83 min "because of the appearance of a hole in the slab right under the pressure vessel [17]."

The multi-spring connection model was used to carry out the simulation of the experimental work, using the continuous connection model shown in Figure 8. In this model, grillage beam elements were connected to reinforcing steel bars within the cores as shown in Figure 13.

Figure 14 shows the comparison between the experimentally measured and analytically predicted structural behaviour of the slab in fire. As can be seen, the behaviour of the prestressed concrete slabs in fire observed from the test is in good agreement with the numerical results in terms of fire resistance time. On the other hand, the experimental and numerical mid-span vertical deflections are different. Basically, beam elements in SAFIR program adopt the Bernoulli's hypothesis which means plane section remains plane so that shear deformation is not captured; and anchorage, bond and spalling effects care also not taken into account [11]. The difference with respect to vertical deflections, therefore, is attributed to these factors.

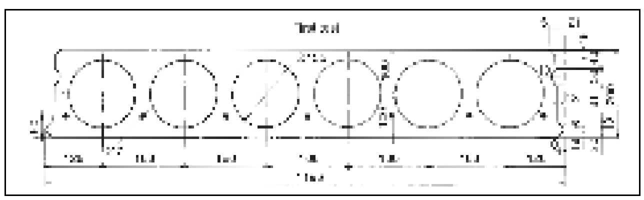


Figure 12. Cross-section of the chosen test unit [17]

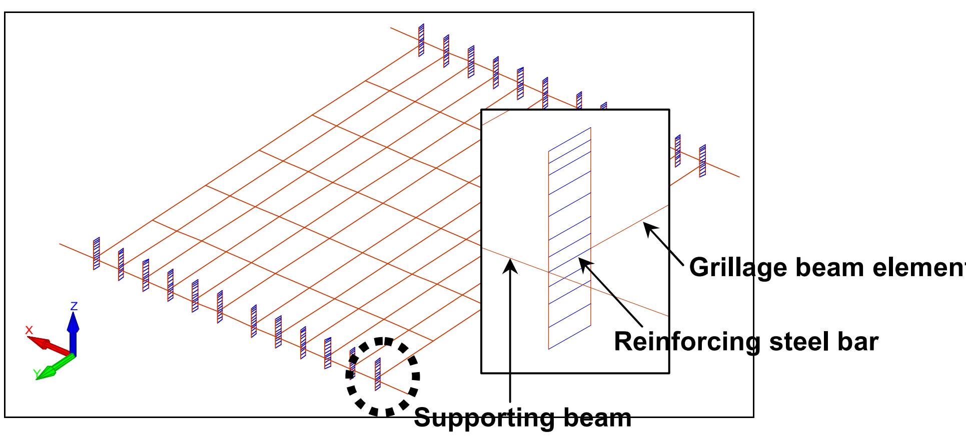


Figure 13. Modelling of the prestressed hollowcore slabs for the test

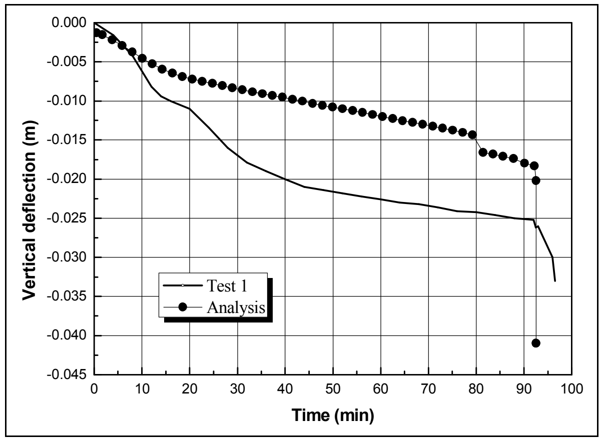


Figure 14. Comparison of structural behaviour against time

CONCLUSION

- The traditional approach of modelling fixed-fixed end condition cannot predict the structural behaviour of prestressed flooring systems in fire.
- A multi-spring connection model has been developed to predict the end connection behaviour of prestressed hollowcore slabs under fire exposure.
- Comparison of analytical results using the traditional approach and the newly developed multi-spring connection models has been made.
- The newly developed multi-spring connection model accounts for the yielding of starter bar or reinforcing steel bar between the prestressed units and the supporting beams.
- The model has been validated against an experiment, which showed good agreement in terms of fire resistance time.
- The newly developed multi-spring model can potentially be utilised to investigate the global behaviour of multi storey buildings in fire.

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